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Fast Determination of the Material Removal Characteristics in Pulsed Electrochemical Machining

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Abstract

Electrochemical machining (ECM) of metallic materials is a complex manufacturing process. Currently the design of the process parameters and the cathode geometry is determined by expensive and inefficient experiments. This paper introduces a method for a fast determination of the material removal characteristics in pulsed electrochemical machining (PECM). The determination is performed by help of removal experiments using a PEMCenter 8000. As example the material removal characteristics of stainless steel 1.4301 under PECM conditions are shown. Based on the resulting mathematical description of the material removal characteristics a design of PECM processes by analytical calculations or multiphysics simulation is feasible.

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Keywords: electrochemical machining, precise electrochemical machining, localized anodic dissolution, material removal characteristics

1. Introduction

The manufacturing process of ECM is based on the principle of anodic metal dissolution and enables processing of metallic materials regardless of their mechanical properties [1-4]. This makes it possible to process difficult to machine materials, since the removal behavior is influenced only by the chemical properties of the materials in combination with the applied electrolyte.

Currently it is a high challenge to describe material-specific removal when deducing the cathode geometry and the process parameters [5]. Thus, most users of ECM conduct extensive empirical test series as basis for designing the cathode geometry regarding the precise representation of geometrical shapes in workpieces and the machining process [6,7]. These test series are time-consuming and inefficient concerning the consumption of workpiece material and energy.

Therefore, this study presents a method to deduce the material-specific dissolution characteristics of materials by characterizing the material removal. The removal function is determined by systematic removal experiments using the ECM variant PECM.

The PECM process is characterized by an oscillating working distance and a pulse current. Due to these facts a higher stability as well as smaller working distance are achievable. [1,6]

2. Method

Certain research [5,6] showed that in ECM the description of the occurring working distance between anode and cathode is characterized by the effective material removal rate V_{eff}. Currently V_{eff} is determined by the mass removal m_a and the transported charge quantity Q according to equation 1 [1,5,8,9,10,11,12].

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$$V_{eff} = \frac{m_a}{Q \cdot \rho} \tag{1}$$

In order to determine the removal mass m_a, the anode has to be weighed before and after every experiment. This method of weighing is time-consuming.

Using the dissolution rate in z-direction v_a and current density J, V_{eff} can be determined faster. Equation 2 shows this connection resulting from Faraday's law.

$$V_{eff} = \frac{v_a(J)}{J} \tag{2}$$

Since the material-specific dissolution rate in z-direction v_a is not directly available as a measured variable, it was reproduced onto the feed rate v_f of the cathode in the desired characterization of the material removal.

For PECM the feed rate is superimposed with an oscillation of the cathode. As shown in figure 1, the applied pulsed current is only triggered on the bottom dead center of the oscillation during processing. Thus, the dissolution takes place with a minimum working distance. This pulsed current is characterized by the duty cycle c which is identified by the frequency f_p and by the pulse on time t_{on}.

$$c = f_p \cdot t_{on} \tag{3}$$

Due to the pulsed current the dissolution rate in z-direction v_a takes place in the pulse on time and stop in the pulse off time. In contrast the cathode has also a feed rate during pulse off time. Therefore the feed rate v_f and dissolution rate in z-direction are only equal on average. Considering the pulsed current the prerequisite of an equilibrium distance is according to equation 4.

$$v_f = v_a(J) \cdot c \tag{4}$$

Considering the duty cycle, the resulting V_{eff} for PECM is defined as follows:

$$V_{eff} = \frac{v_f(J)}{J \cdot c} \tag{5}$$

In order to explicitly relate the transported charge Q to the prevailing current density J, a constant current I_{max} over process time t_{Proc} is required as well as a constant removal surface A_a. Consequently, a selected feed rate has to be constant during a removal experiment.

Furthermore, a homogeneous current density is required for the investigated working distance s. Thus material removal shall be reduced to front face removal so that only a front working distance s_F results. When considering these determinations, the current density J can be calculated by the process current I_{max} and the transported charge Q can be calculated by the trend of the process current $I = f(t_{\mathrm{Proc}})$.

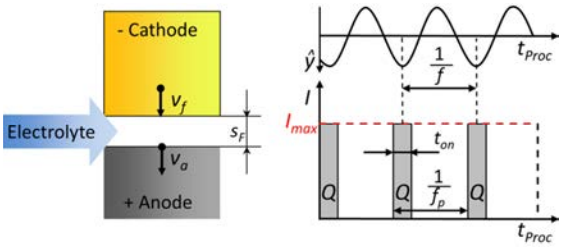

Fig. 1. Schematic representation of removal concept (left) and required current characteristic $I = f(t_{Proc})$ during process (right)

Figure 1 (left-hand side) shows the concept of an EC process with front face removal and transverse flushing.

3. Experimental Setup

The removal device derived from the preliminary considerations was designed to be used in the EC manufacturing machine PEMCenter 8000. Using this removal device it is possible to determine the dissolution characteristic of cylindrical specimens. Figure 2 presents a cross-section of the removal device.

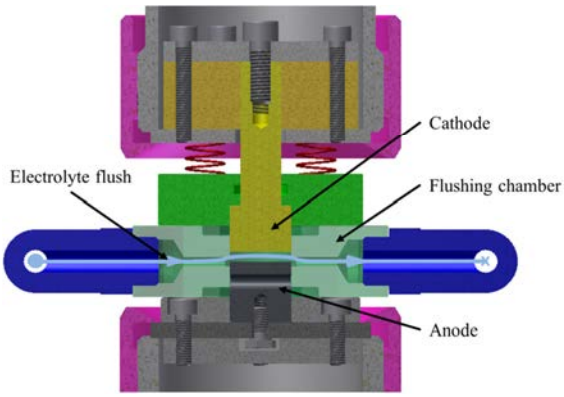

Fig. 2. Sectional representation of removal device with shown flushing direction of the electrolyte

Figure 2 shows the removal device with a cathode (yellow) and an anode (gray) with identical diameter and surface area. The flushing chamber allows for electrolyte flow to provide material removal preventing slag formation.

During the performance of experiments under PECM conditions, the process parameters are measured such as electrical current, characteristic parameters of the electrolyte and the final working distance.

4. Design of Experiments

Several process parameters were kept constant throughout the investigations. These process parameters are summarized in Table 1. Stainless steel 1.4301 was selected to demonstrate the fast determination of the material removal characteristics in PECM. Its specific removal volume V_{sp} was calculated of $2.33 \cdot 10^{-5}$ cm³/C. A solution of $NaNO_3$ with a salt content of

8% was used as electrolyte. The oscillation frequency and the pulse frequency were selected to be 50 Hz.

Table 1. Constant parameters

Symbol	Parameter	Value
	Anode material	1.4301
d	Anode diameter	12 mm
l	Anode length	12 mm
	Electrolyte	Sodium nitrate
σ	Electric conductivity	69 mS/cm ± 0.5 mS/cm
p_{in}	Electrolyte inlet pressure	3.1 bar
p_{out}	Electrolyte outlet pressure	0.5 bar
f	Oscillation frequency	50 Hz
f_p	Pulse frequency	50 Hz

In the investigations should be achieved a range of current density J between 10 A/cm² and 110 A/cm² and front working distance s_F between 10 µm and 100 µm. For this purpose several process input parameters were varied. Table 2 summarizes these input parameters.

Table 2. Experimental parameters

Symbol	Parameter	Value
U_q	Voltage	5 – 14 V
v_f	Feed rate	0 – 0.5 mm/min
t_{on}	pulse on time	1 ms; 2 ms; 3 ms; 4 ms

After first removal experiments a preliminary function of $v_f = f(J)$ can be derived. Thereby it is possible to calculate the feed rate v_f for a desired current density. Due to the known current density and removal area the expected current in the removal process can be calculated. This value has to set during removal process by changing the voltage parameter.

5. Experimental Results

Figure 3 demonstrates the feed rate as a function of the current density for the investigated pulse on times t_{on} of 1 ms, 2 ms, 3 ms and 4 ms. It is obvious that the feed rate increases linearly with the increase of electrical current density.

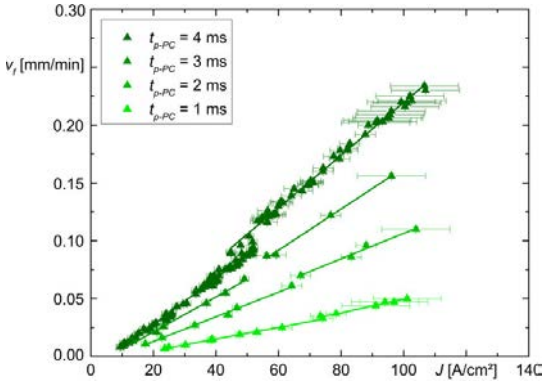

Fig. 3. Feed rate as a function of the current density at different pulse on times for 1.4301 in $NaNO_3$ electrolyte with salt concentration of 8%

Different increases of the characteristics occur for the investigated pulse on times t_{on}. The higher the pulse on time is, the higher is the increase of the characteristics. Furthermore, a discontinuity can be found. The range of current density in which the discontinuity occurs depends on the pulse on time. Moreover, a minimum current density is apparent which varies for the individual functions. In order to characterize the material 1.4301, the removal rate in z-direction was calculated as a function of current density. This is shown in Figure 4.

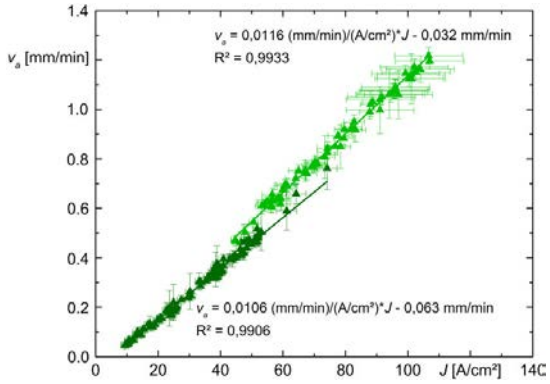

Fig. 4. Removal rate in z-direction as a function of the current density

It is evident that the removal rate in z-direction v_a increases linearly with the current density J. In this case the removal experiments with the applied pulse on times t_{on} are subordinate to this linear course. This allows the conclusion that the removal characteristic is independent from the duty cycle c. Moreover, in the case of the removal experiments a discontinuity of the characteristic is exhibited in the current density range between 44 A/cm² and 74 A/cm². This discontinuity probably indicates a change of electrochemical valency of elements. The existing correlation between the removal rate in z-direction and the current density can be described by two linear correlation functions according to equation 6.

$$v_a(J) = V_m \cdot J + v_0 \tag{6}$$

Table 3 shows the parameters of the derived correlation functions.

Table 3. Parameters of the correlation function

	$J\left[\frac{A}{cm^2}\right]$	$V_m\left[\frac{mm/min}{A/cm^2}\right]$	$v_0\left[\frac{mm}{min}\right]$	Correlation coefficient R^2
1	9 – 74	0.0106	-0.063	0.9906
2	45 – 107	0.0116	-0.032	0.9933

The parameter V_m describes the removal volume of stainless steel 1.4301 in the electrochemical dissolution in a $NaNO_3$ solution with a salt content of 8% in DC processing. The lower range of current density from 9 A/cm² to 74 A/cm² results in a removal volume $V_{m\text{-}1}$ of $1.77 \cdot 10^{-5}$ cm³/C, and the upper range of current density from 45 A/cm² bis 107 A/cm² has a resulting removal volume $V_{m\text{-}2}$ of $1.93 \cdot 10^{-5}$ cm³/C. In comparison, the theoretical specific removal volume V_{sp}

amounts to $2.33 \cdot 10^{-5}$ cm³/C. Thus a maximum current efficiency of approx. 83% can be expected for the upper current density range. The parameter v_0 describes the point of intersection with the y-axis. Since this parameter is negative, a minimum current density of 5.9 A/cm² can be derived. This theoretically parameter describes approximately the beginning of the material removal. Using this data a transpassive material dissolution can be derived. Under PECM conditions the removal rate in z-direction $v_{a\text{-}PC}$ is defined as follows:

$$v_{a-PC} = v_f = (V_m \cdot J + v_0) \cdot c \tag{7}$$

In order to evaluate the accuracy of the method the current efficiency $\eta_{m\text{-}a}$ was calculated by determining the removal mass, using mass weighing according to equation 8.

$$\eta_{m-a} = \frac{m_{eff}}{m_{sp}} = \frac{m_a}{m_{sp} \cdot Q} \tag{8}$$

This was compared to the current efficiency $\eta_{v\text{-}a}$, which was derived by using the determined removal rate in z-direction $v_a = f(J)$.

$$\eta_{v-a} = \frac{v_a(J)}{V_{sp} \cdot J} \tag{9}$$

Figure 5 shows the two determined current efficiencies as functions of the current density for PECM of 1.4301. In addition, the function of current efficiency $\eta_{v\text{-}a} = f(J)$ is shown, derived from the function curve of the removal rate in z-direction v_a according to equation 9.

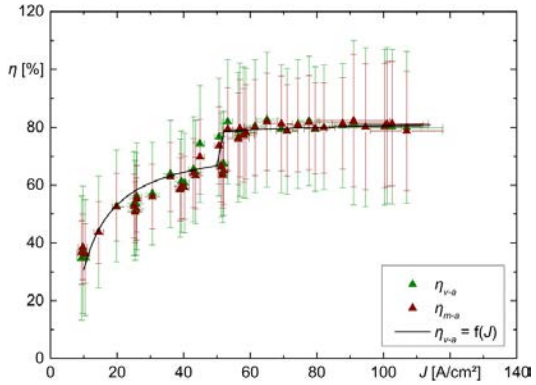

Fig. 5. Comparison of the determined efficiencies $\eta_{m\text{-}a}$ and $\eta_{v\text{-}a}$ as a function of the current density for a pulse on time of 4 ms

Figure 5 demonstrates that the current efficiency increases with rising current density until the transition behavior of the removal function is reached in a current density range between 45 A/cm² and 52 A/cm². At current densities higher than 52 A/cm² the current efficiency amounts approx. 80%. The current efficiencies derived from mass removal or feed rate show comparable behavior. For the investigated pulse on times the deviation of the current efficiency amounts to ±4%.

6. Summary

Within this study a method for fast determination of the material removal characteristics in pulsed electrochemical machining was shown and validated by experiments. In this context, the removal behavior of the material 1.4301 was characterized. Transpassive material dissolution was proven, possibly starting at a current density of 5.9 A/cm². A linear function between feed rate and current density for different pulse on times was shown. Furthermore, a discontinuity of the removal function was determined. The range of current density in which the discontinuity occurs is influenced by the pulse on time. In addition, a correlation was derived for calculating the removal rate in z-direction under PECM conditions. Furthermore, the presented method was compared to mass weighing. Thereby an accuracy of ±4% when applying the fast determination of the material removal characteristics was found.

Acknowledgements

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